Interferometry in Space

Poster #4825-65

Automatic alignment of the heterodyne interferometer for SIM

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Abstract

We developed and tested a technique for automatically aligning the beams of displacement-measuring interferometric gauges. The pointing of the launched beam is modulated in a circular pattern and the resulting displacement signal is synchronously demodulated to determine the alignment error. This error signal is used in a control system that maintains the alignment for maximum path between a pair of fiducial hollow-cube corner retroreflectors, hence minimizing sensitivity to alignment drift. The technique is tested on a developmental gauge of the type intended for SIM, the Space Interferometry Mission. The displacement signal for the gauge is generated in digital form, and the lock-in amplifier functions of modulation, demodulation, and filtering are all implemented digitally.

1. Introduction

The target metrology accuracy for SIM, the Space Interferometry Mission, is approximately 10^{-11} radian. A key element of SIM is a cluster of displacement-measuring heterodyne interferometer gauges that monitor changes in the separation of telescope mirrors. These gauges must be linear and repeatable to approximately 10 picometer (pm) as the optical paths change by as much as 1 m. One source of astrometric error is inaccuracy or drift in the orientation of the optics that launch the $\lambda = 1.3$ micron wavelength laser beam. The optics will be mounted on the spacecraft structure, which may have a deployment error on the order of 1 milliradian and be unstable at the level of 10 microradian. We describe a control system designed to sense and reduce initial error and drift to approximately 10 microradian and 1 microradian, respectively—the levels needed to meet the overall gauge requirement.

The control system implements control with a lock-in amplifier: mechanical modulation of the launch angles (θ, ϕ) and synchronous demodulation of the path-length output of the gauge. Since the SIM gauges generate their output in digital form, we implement the lock-in amplifier digitally, and use digital filters for the control system.

2. Path-length change due to beam tilt

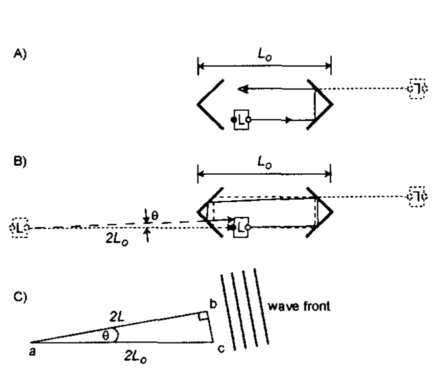

FIGURE 1: *The measurement of interest is the optical path between a pair of fiducial hollow-cube corner retroreflectors. For two cube corners, as the launch angle changes away from parallel to the line joining the vertices of the two cube corners, the reference plane rotates so that the two perpendicular distances become shorter, and the measured distance between two corner cubes decreases. The launcher is shown as the dark-lined boxed L-symbol. The distance between fiducial reflectors is L_0. Sub-figure (A): After striking the right reflector and returning to the the plane of launch, the image of the launcher is inverted (short dashed lines). (B): The beam returns to the launcher after reflecting from the left reflector. The upright image has traveled $2L_0$ (short dashed line to left of left reflector). When the launched beam is tilted by θ with respect to the line joining the reflector vertices, the beam follows the path of the long-dashed line. The misalignment by θ corresponds to the launcher image being tilted by θ; this is represented by a the tilted wavefront in (C). The approximation of a nearly-parallel wavefront is valid, since the displacement due to misalignment bc is small compared to the spot radius. The distance $2L$ that the wavefront travels before reaching the aperture at c is shortened relative to the distance $2L_0$ that an aligned wavefront would travel: $2L = 2L_0 \cos\theta$.*

If the launch angle deviates by θ from the line to the vertex, the measured path changes by $L = L_0 \cos\theta$, where L_0 is the distance to the vertex. Since θ is small, length changes can be approximated by $\Delta L \approx -(L_0/2)\theta^2$.

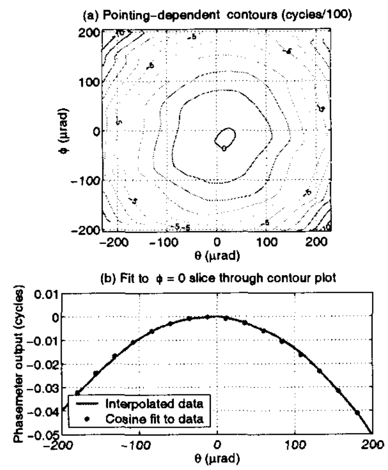

FIGURE 2: *The quadratic dependence on θ was verified by scanning the launch angle by as much as $2 \cdot 10^{-4}$ radian in two axes, and simultaneously monitoring the gauge output.*

Considering the alignment error as composed of static misalignment θ_0 and a fluctuation $\Delta\theta$, path changes can be approximated by

$$\Delta L = -L_0 \theta_0 \Delta\theta. \tag{1}$$

3. Implementation of control

The output beam angle is mechanically modulated by angle by $\Delta\theta$. The measurement system responds by changing an amount ΔL modulation frequency, proportional proportional to misalignment θ_0.

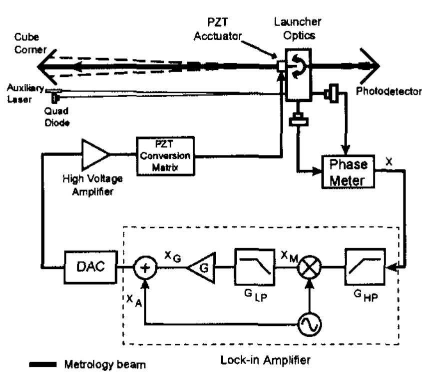

FIGURE 3: *A pointing actuator modulates the beam in a circular pattern at 2.5 Hz, with diameter 60 microradian. The fiducial cube corners are separated by 70 cm. The interferometer beam executes a round trip and is interfered with the launched beam; the interference is detected on a photodiode. Length measurement is based on the heterodyne technique: A 100 kHz frequency shift between the launched beam and a reference beam imposes an interferometric phase shift on the detected signal that is proportional to the length traversed by the beam. The phase-meter consists of analog filters and specialized digital hardware that converts the phase shift into displacement, generating a digital signal proportional to the path length x. The two tilt angles θ and ϕ are detected separately by demodulating in-phase (shown) and in quadrature (not shown). The block enclosed within the dashed lines is a digital lock-in amplifier. A digital-to-analog converter (DAC) and high-voltage amplifier drive the piezoelectric actuator (PZT) with the sum of the correction signal and modulation.*

4. Control system performance

Since the modulation and correction are at frequencies below the first mechanical resonance of the system, the frequency-dependence is contained entirely in the single-pole low-pass filter. The closed-loop step response is then

$$p(t) = \frac{k}{1+k}\left(1 - \exp(-\frac{(1+k)t}{\tau}\right) \tag{2}$$

The gain was varied under software control within the range $10 < k < 200$. The expected drifts on SIM require $k \geq 10$.

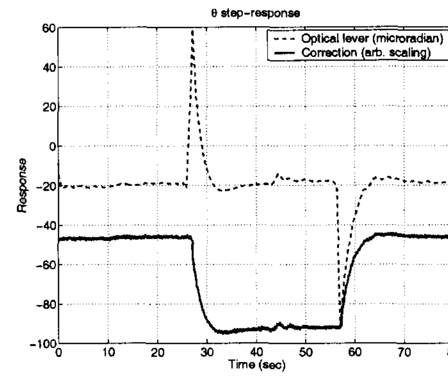

FIGURE 4: *Control system response to an imposed step disturbance in the launcher pointing. The optical lever θ signal records the transient response and recovery, and the θ correction signal shows the step change in voltage required to track the cube corner position. For this test, the filter time constant was $\tau = 1.6 \cdot 10^3$ sec, and the gain was $k = 200$. The launcher pointing angle returned to within 1% of the imposed disturbance. The large value of τ implements a control law that is equivalent to an integrator at most time-scales of interest.*

5. Closed-loop stability

The performance of the control system was measured by an optical lever consisting of an external laser 52 cm from the launcher that strikes a mirror affixed to the launcher housing, and a quadrant photodiode adjacent to the laser that intercepts the reflected beam. The processed quadrant photodiode signal provides a measure of the launcher pointing that is independent of the controlled signals.

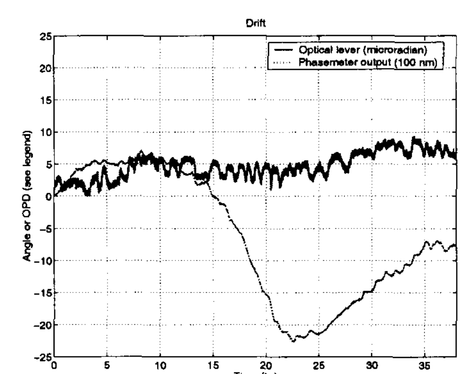

FIGURE 5: *The peak-to-peak drift over 40 hours, as measured by the optical lever, was 8 μrad. This is to be compared with the SIM requirement of average variation not to exceed 1 μrad over times of approximately 1 hr.*

The launch angle of the optical lever was shown in separate measurements to drift by an amount approximately the same as the observed drift, so we conclude that the measured drift is an upper limit. Demonstrating the required stability will require improving the optical lever performance, possibly by improved thermal stabilization. In addition to the drift, a relatively high-frequency variation in pointing angle is imposed by the control system. This variation is sinusoidal in the measured optical-path x, with frequency $2x/\lambda$ and peak-to-peak amplitude of approximately 3 μrad; the mechanism is under investigation. Future experiments with multiple gauges will test the absolute pointing requirement of 10 μrad.

6. Acknowledgements and Reference

Frank Loya provided essential support in developing the final version of the control and data collection software. This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration. This work is described in the recently published paper, J. E. Logan, P. G. Halverson, M. W. Regehr, and R. E. Spero, "Automatic alignment of a displacement-measuring heterodyne interferometer", Appl. Opt. **41**, 4314–4317 (2002).